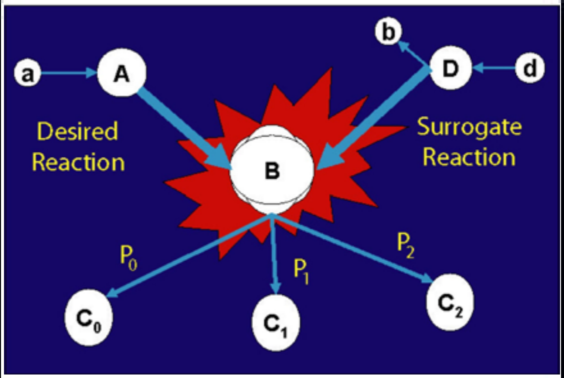
Surrogate Nuclear Reactions: Trying to do the impossible

Physics and Advanced Technologies



Workshop on “Nuclear Reactions on Unstable Nuclei and the Surrogate Reaction Technique

Jan 12-15, 2004, Asilomar

Erich Ormand

Nuclear Theory & Modeling

Lawrence Livermore National Laboratory

This work was carried out under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

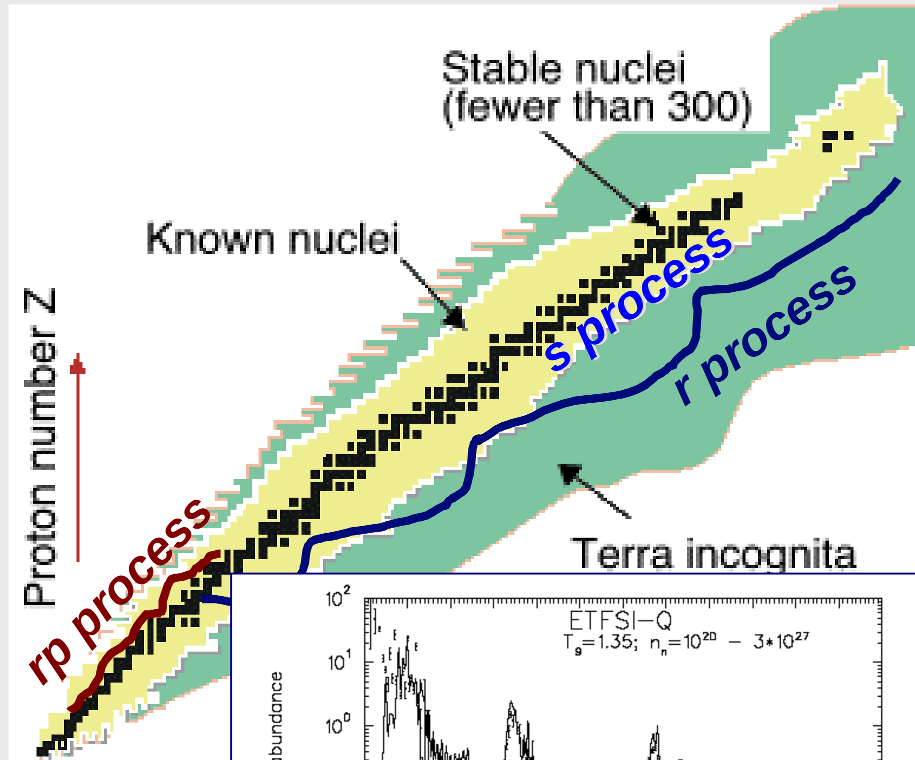
UCRL-PRES-201956

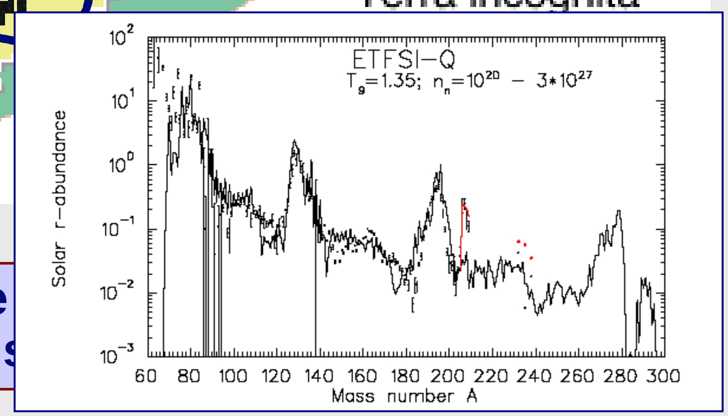
Jan 12, 2004

Reaction networks involve unstable nuclei

"How were the elements from iron to uranium made?" -- one of the 'Eleven Science Questions for the New Century' [*Connecting Quarks with the Cosmos*, Board on Physics and Astronomy, National Academies Press, 2003]

- **Nucleosynthesis**
  - s-process
  - r-process
  - rp-process
- **Stewardship**
  - RadChem diagnostics





Understanding the origin of the requires knowledge of reactions

Disentangling the s- and r-processes…

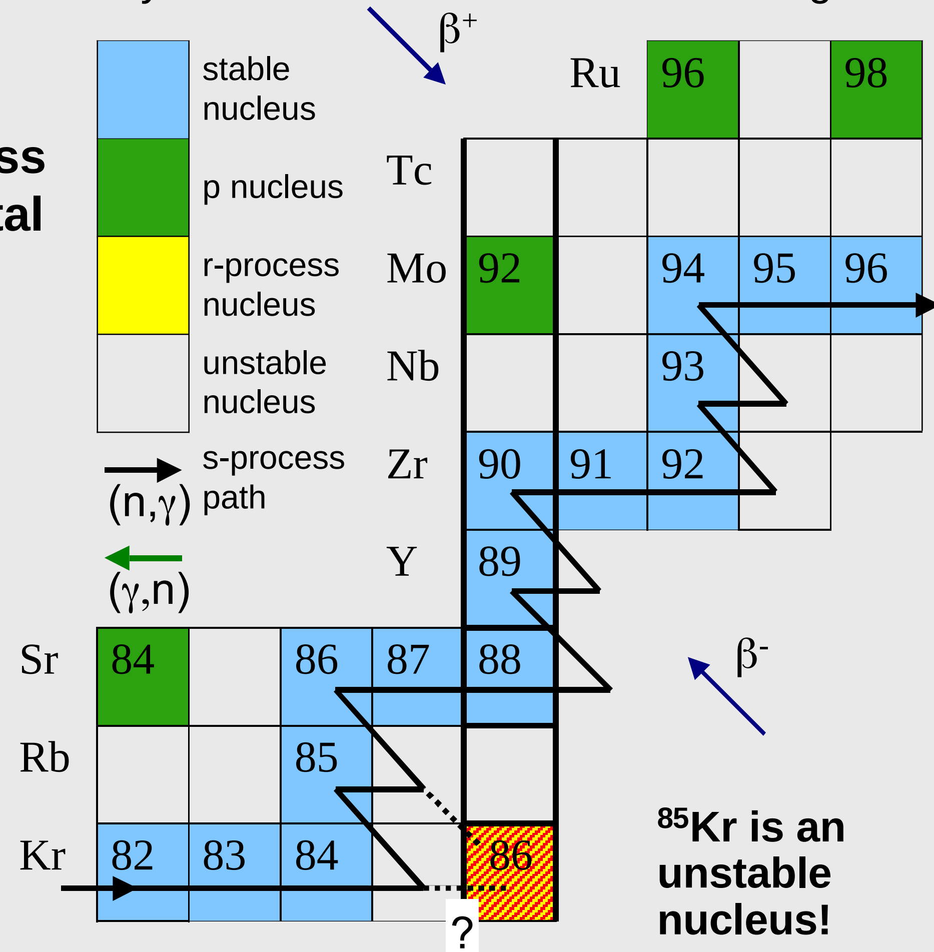
- s-process better known than r-process
- r-process abundances are obtained by subtracting s-process contributions from measured total abundances

Reliable s-process abundances are required to shed light on the issue!

What is the cross section for:

n + ^{85}Kr --> ^{86}Kr* + γ ?

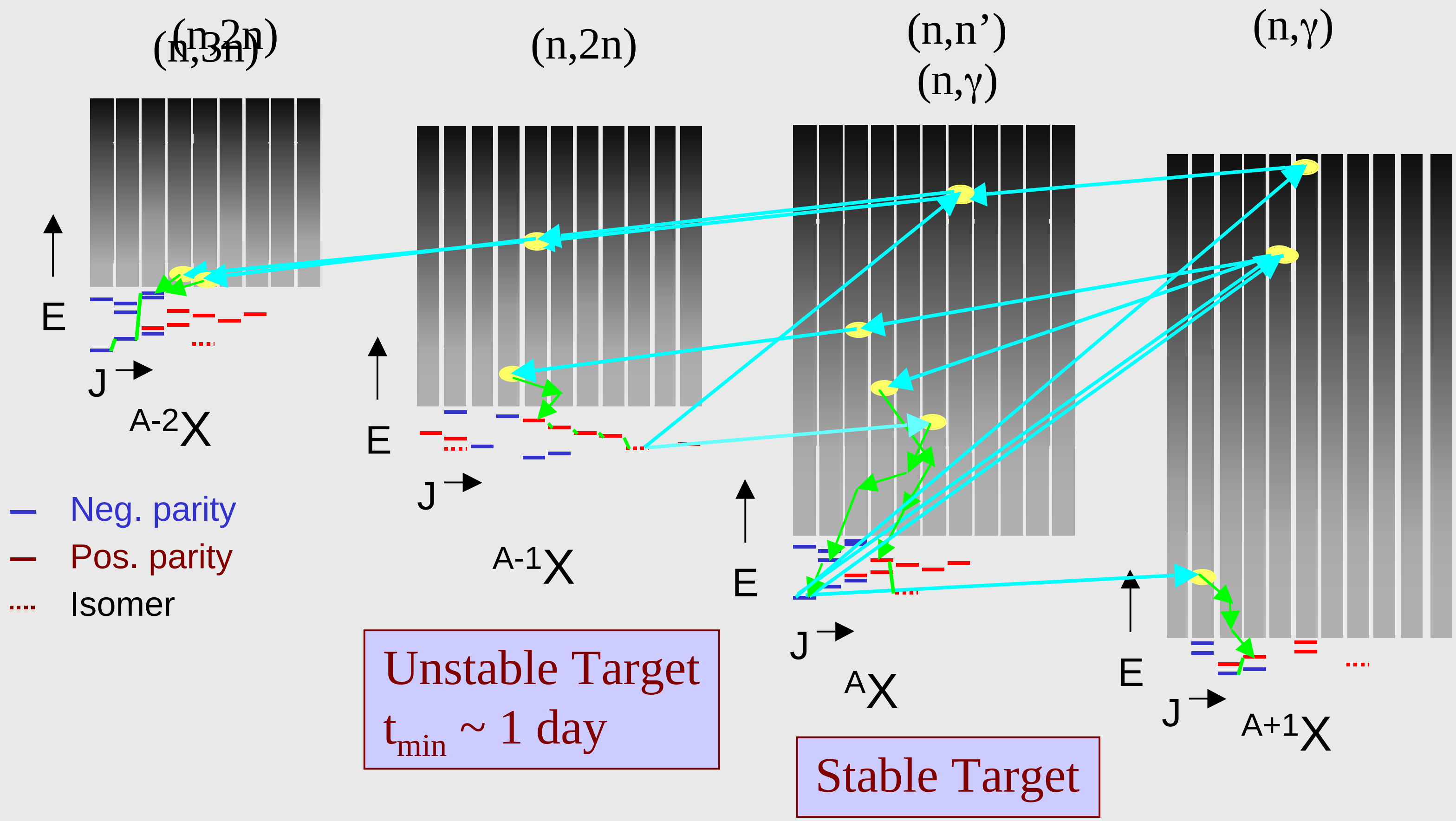
Synthesis of elements in the A=90 region



^{85}Kr is an unstable nucleus!

…requires knowledge of reactions on unstable nuclei!

Reaction networks involve unstable nuclei



Without experiments, we must rely on theory

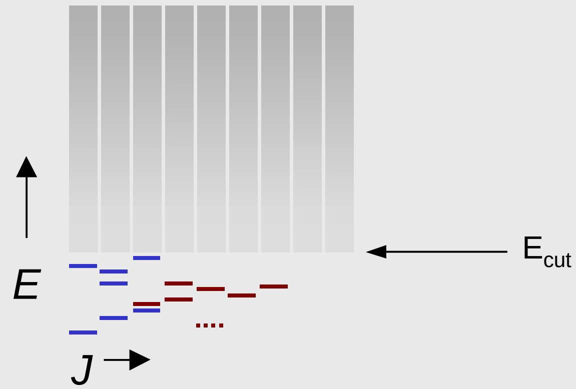
- **Hauser-Feshbach**

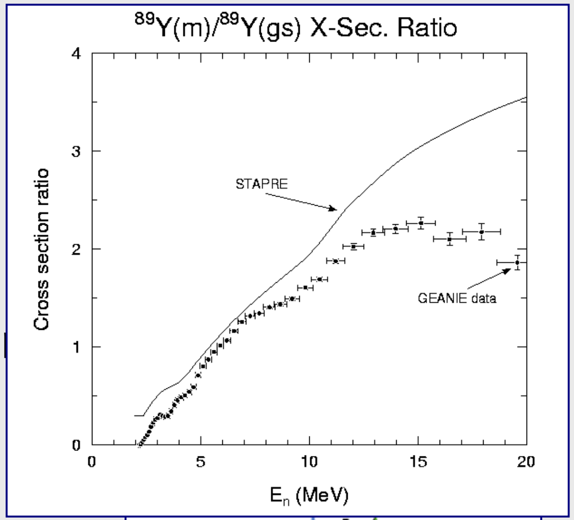
$$\frac{d\sigma_{cc'}}{dE_{c'}} = \sum_{J,\Pi} \sigma_c^{comp} \frac{\sum_{l'} g_{l'J_{c'}} T_{l'}(E_{c'}) \rho\left(E_{c'}^{\max} - E_{c'}\right)}{\sum_{c''l''} g_{l''J_{c''}} T_{l''}(E_{c''}) \int_{o}^{E_{c'}^{\max}} \rho\left(E_{c''}^{\max} - E_{c''}\right) dE_{c''}}$$

$$\sigma_c^{comp} = \frac{\pi}{k_c^2} g_J \left\{ \sum_{s,l} T_l(c) \right\} - \sigma_c^{preeq}$$

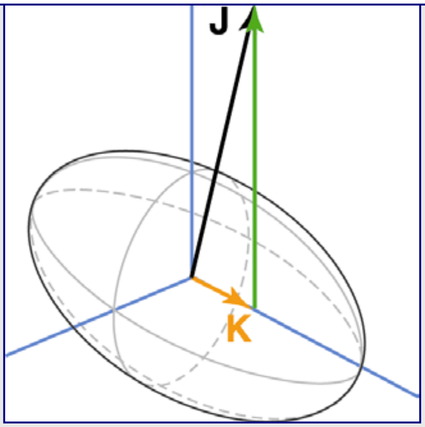
- **Physics inputs**
  - **Level density**
  - **Discrete states**
  - **γ-ray decay path; low-lying discrete spectroscopy, isomers**
    - **Transition from continuous to discrete spectrum**
  - **Transmission coefficients - optical model - far from stability**
  - **Pre-equilibrium cross section - angular momentum deposition**
  - **Fission – predictive model?**

Theory has uncertainties

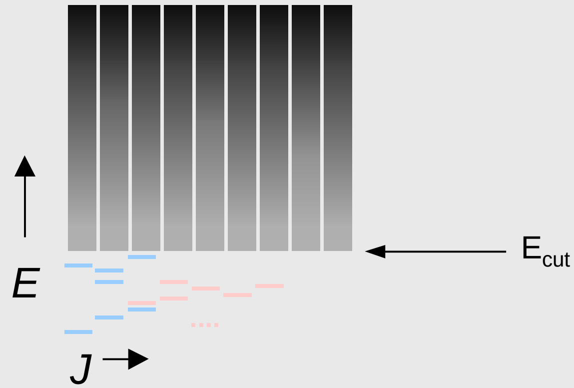




- **Discrete states taken from experiment whe**
  - **Often insufficient**
- **γ-ray decay path**
  - **low-lying discrete spectroscopy**
    - **Critical for determining isomer populations**
  - **Transition from continuous to discrete spectrum**
    - **Statistical decays**
  - **Conservation laws**
    - **K-quantum number**
    - **Isospin**



Theory has uncertainties - Level density

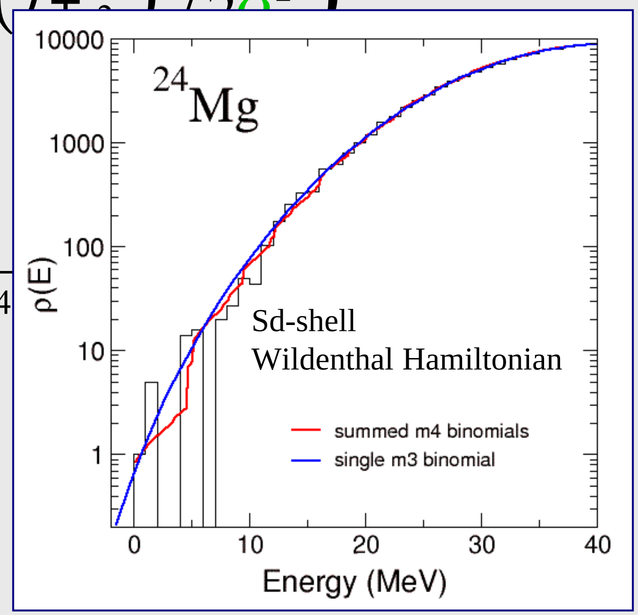


$$\rho(E,J) = \rho(E)(2J+1)\frac{1}{2\sigma^2}\exp\left(-\left(J+\tfrac{1}{2}\right)^2/2\sigma^2\right)$$

- **Low *E* - Exponential :** $\rho(E) = Ae^{E/T}$
- **Higher *E* - Fermi gas :** $\rho(E) = \frac{1}{2\sqrt{2}a^{1/4}}$
- **Microscopic models**
  - **Monte Carlo Shell**
  - **Statistical method**

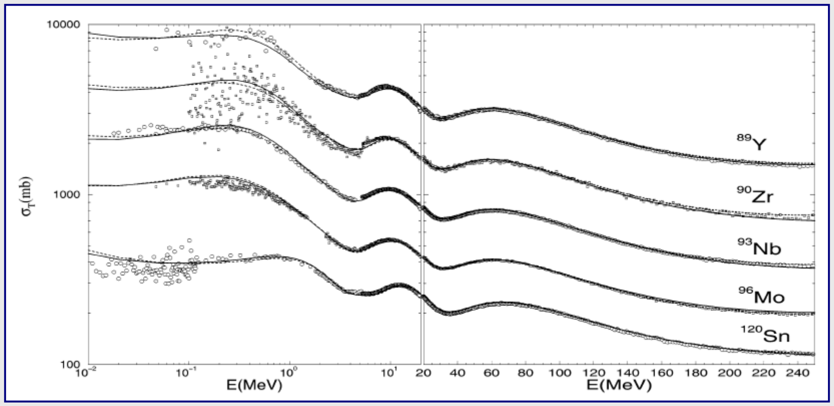
Statistical shell model

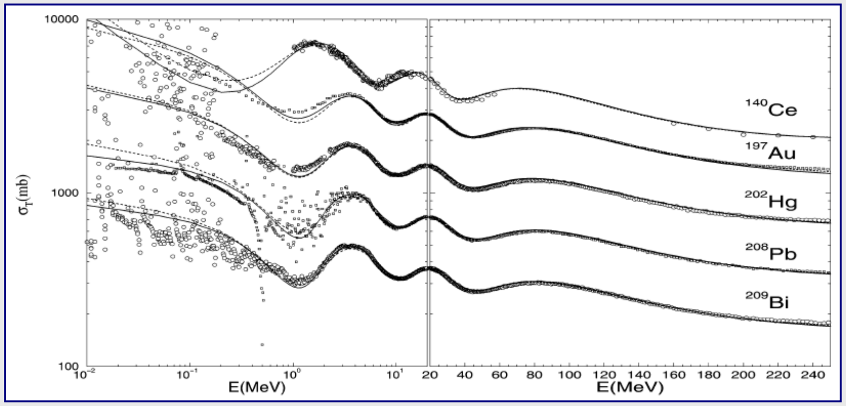
Partitions with 1st, 2nd, 3rd, and 4th moments of H



Theory has uncertainties

- **Transmission coefficients**
  - **Global parameters from Koning and Delaroche, NPA 713, 231 (2003)**

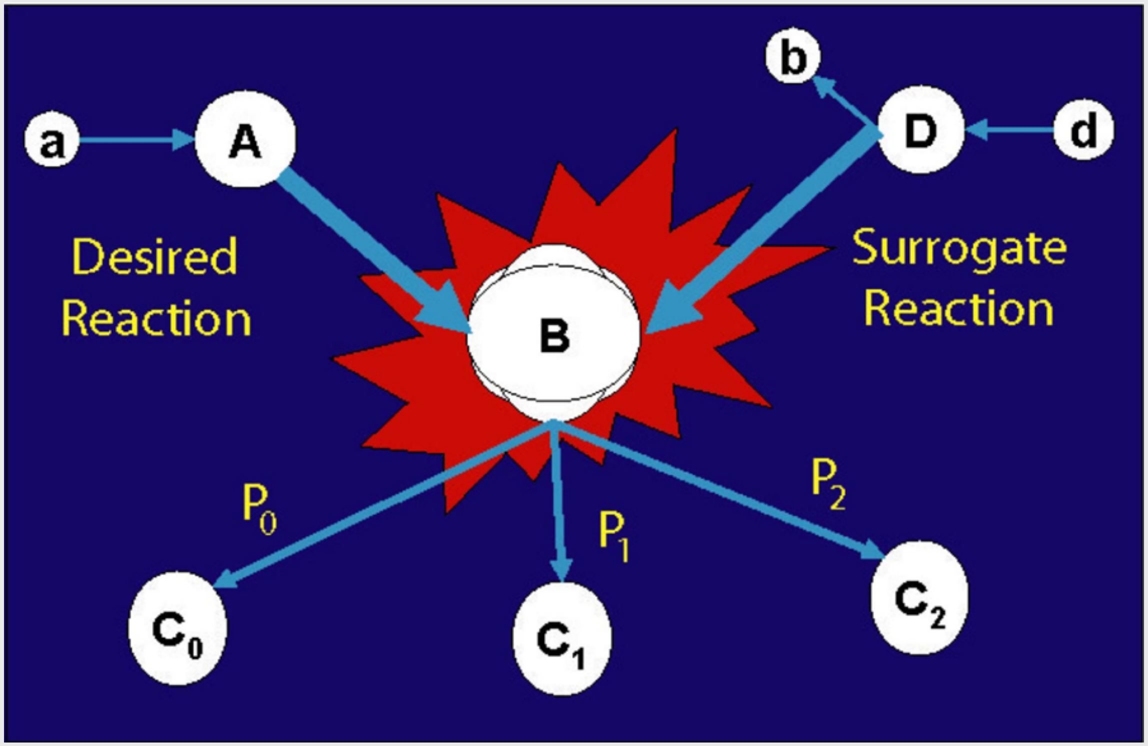




  - **But what do we use far from stability?**
- **Pre-equilibrium**
  - **There is a need for a good, practical microscopic model**
  - **angular momentum deposition**
- **Fission**
  - **Double-barrier penetration models**
    - **Barrier heights, widths, and level densities above the barrier**
  - **There is a need for an accurate, predictive model**

But must we rely only on theory?

- **Rely on the compound nucleus hypothesis to find an alternative mechanism (surrogate) for making the same compound nucleus**
  - **(n,X) → (^{3}He,αX) or (d,pX)**



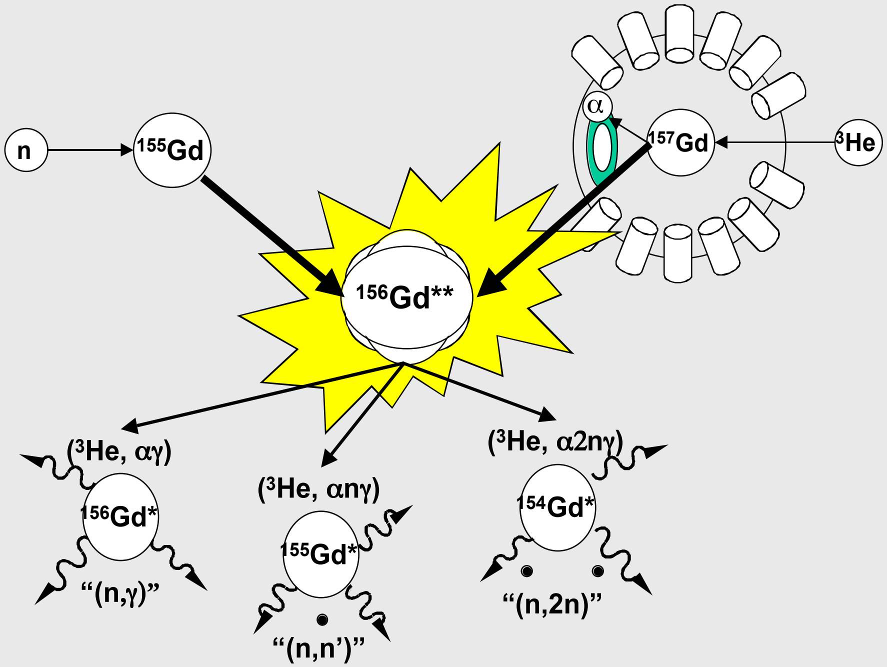
Warning, this won't give the neutron cross section, but it will give us decay probabilities from the compound

Cross sections for unstable nuclei via Surrogate reactions - the ^{156}Gd example & test

The cross section for the desired two-step reaction

$$n + {}^{155}\mathrm{Gd} \rightarrow {}^{156}\mathrm{Gd}^{**} \rightarrow {}^{156}\mathrm{Gd} + X$$

can be determined indirectly with the Surrogate method.



The compound nucleus ^{156}Gd is produced in an initial reaction using a stable ^{157}Gd target:**

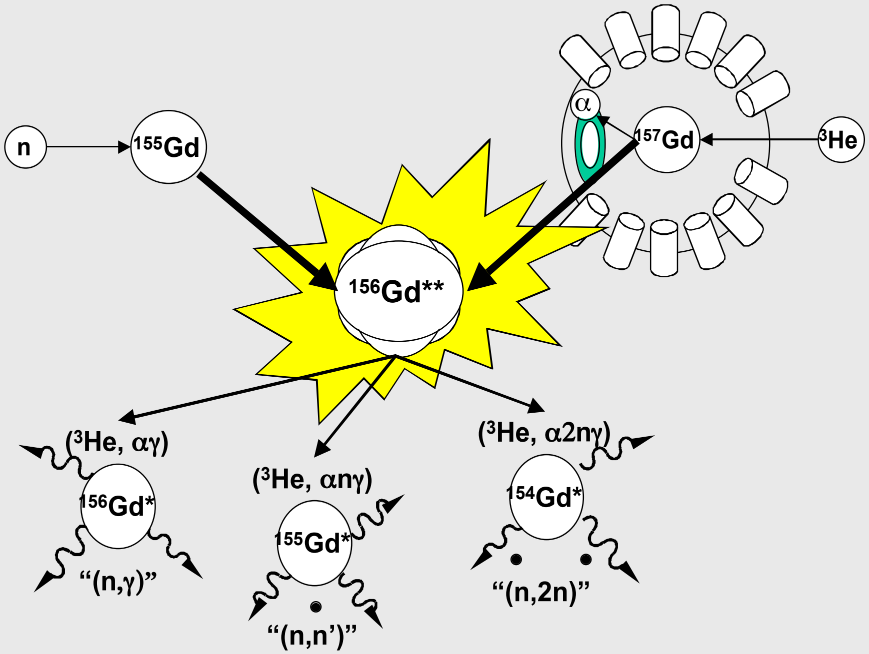
$$^{3}\mathrm{He} + {}^{157}\mathrm{Gd} \rightarrow {}^{156}\mathrm{Gd}^{**} + \alpha$$

$$^{156}\mathrm{Gd}^{**} \rightarrow {}^{155}\mathrm{Gd}^{*} + n + \gamma + \ldots$$

From the decay of ^{156}Gd we can infer the desired cross section.**

Cross sections for unstable nuclei via Surrogate reactions - the ^{156}Gd example & test

- **Detect α-particle to tag the compound system and energy**
- **Measure γ in final nucleus in coincidence with α**
  - **Ratio of number of γ and α gives decay probability to final channel**
  - **$2^+ \rightarrow 0^+$ acts as a collector in ^{156}Gd**



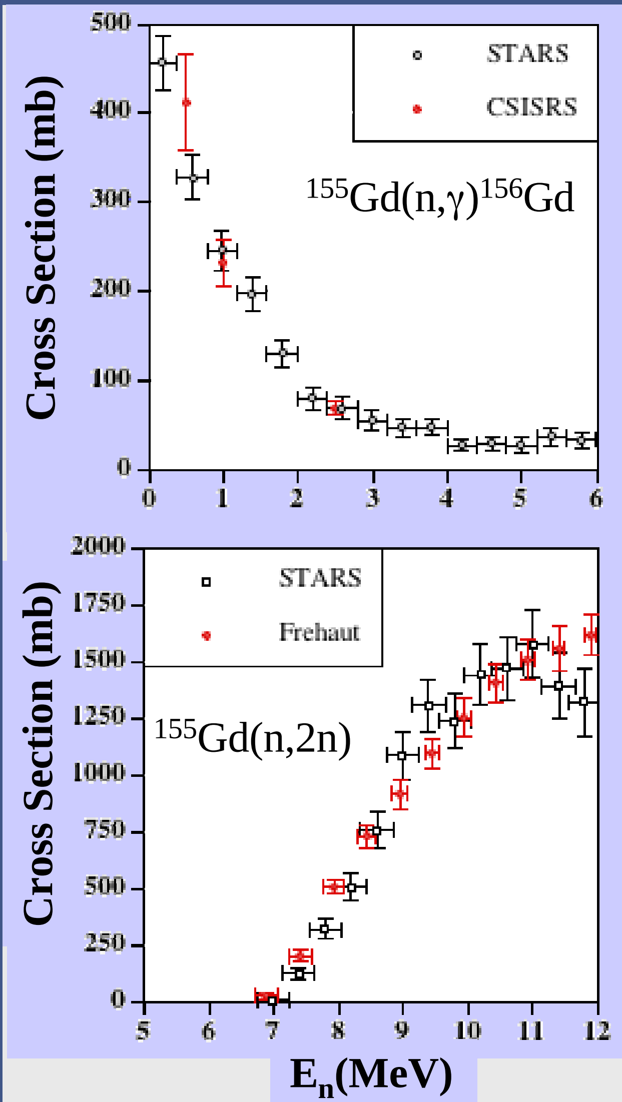
$$P_\gamma^{CN}(E) = \frac{N_\gamma^{2^+ \rightarrow 0^+}}{N_\alpha}$$

$$\sigma_{(n,\gamma)}(E) = \sigma^{CN}(E) P_\gamma^{CN}(E)$$

Ignore angular momentum for now

- **σ^{CN} calculated with the optical model**
  - **Theory is still needed**

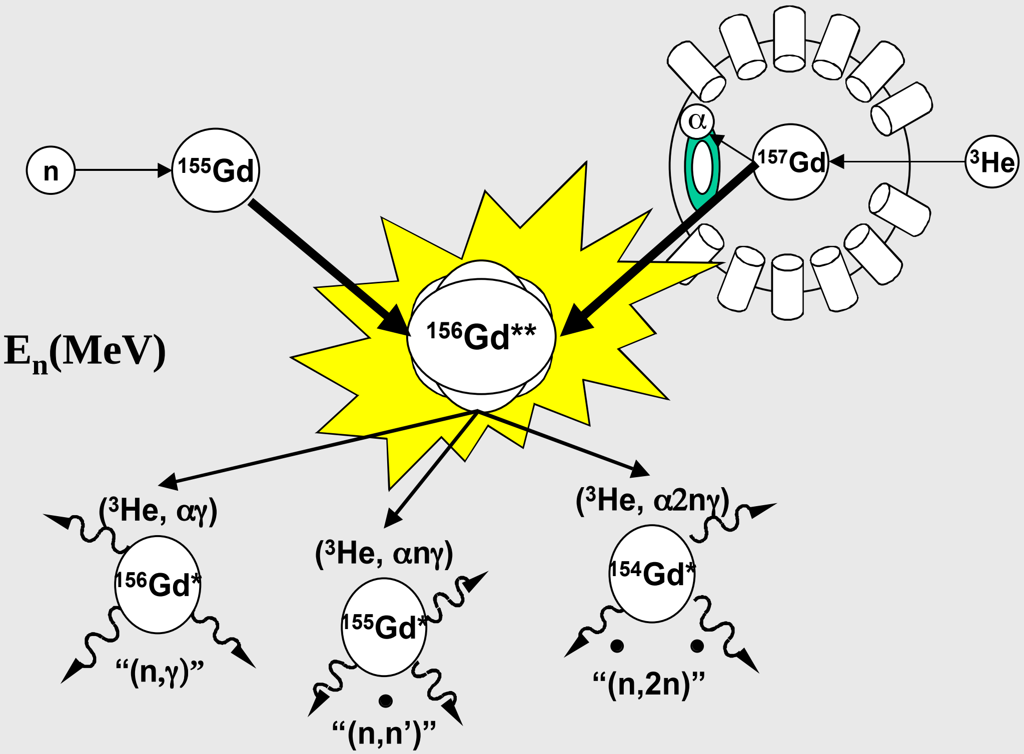
Validating the Surrogate technique



← Surrogate measurement using ^{157}Gd(^{3}He,α)

← Direct measurement

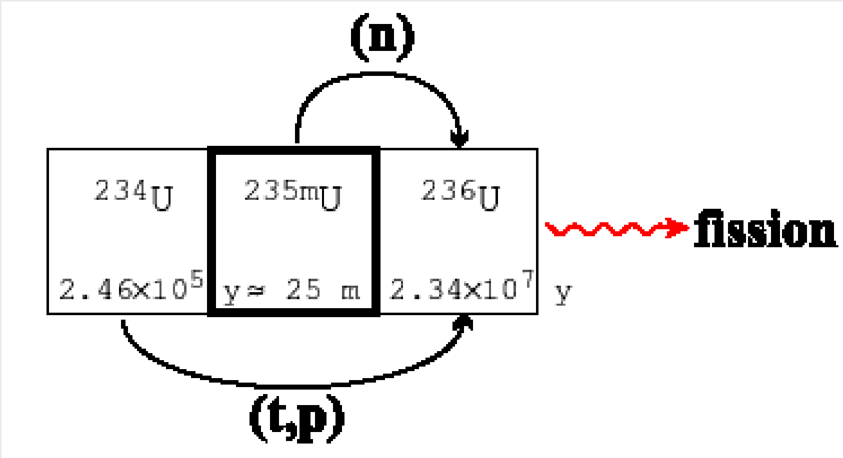
E$_n$(MeV)

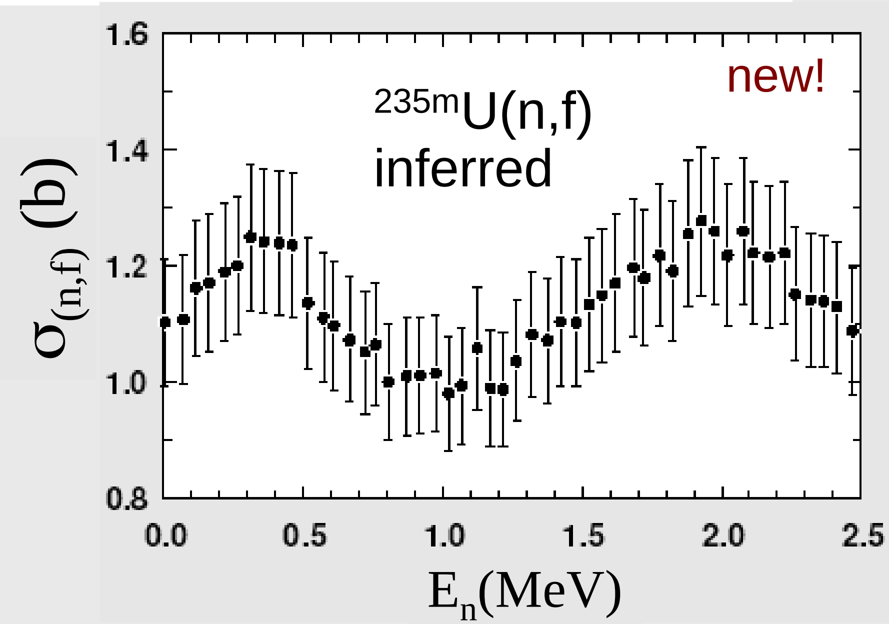


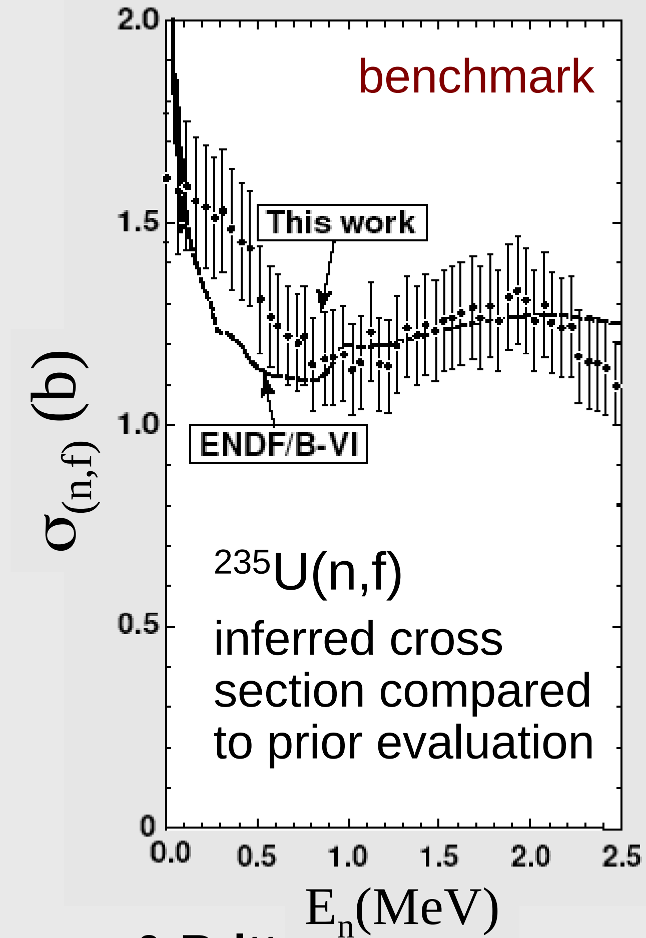
Bernstein *et al.*, analysis in progress

Experiment carried out in Berkeley

Applying the Surrogate technique - actinide nuclei







Younes & Britt,
PRC <u>67</u> (2003) 024610,
PRC <u>68</u> (2003) 034610

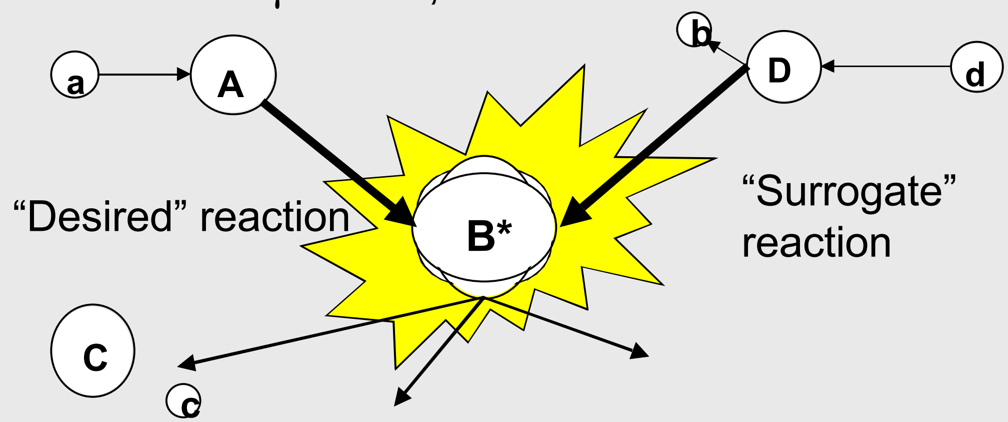
Challenges: Angular momentum

Ideal:

Cross section for two-step process: $\sigma_{\alpha\gamma} = \sigma_\alpha^{CN}(E) \cdot P^{CN}_\gamma(E)$

$\sigma_\alpha^{CN}(E) = \sigma(a+A \to B^*)$ - can be calculated

$P^{CN}_\gamma(E)$ - probability for decay into channel γ = c+C, can be determined from Surrogate experiments



Reality:

Cross section for a+A -> B* -> c+C : $\sigma_{\alpha\gamma} = \Sigma_{J,\pi}\, \sigma_\alpha^{CN}(E,J,\pi) \cdot P^{CN}_\gamma(E,J,\pi)$

J - angular momentum of compound nucleus B*

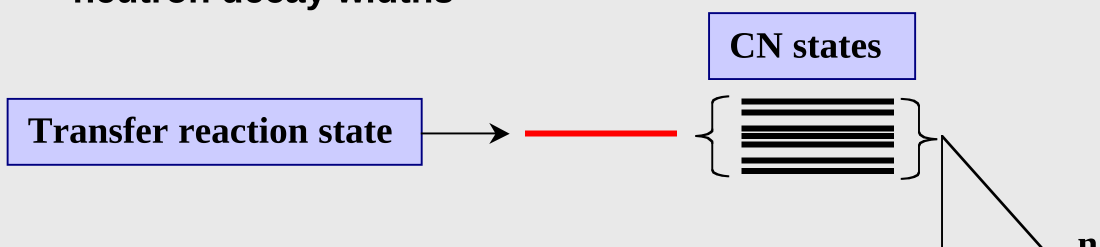
$\sigma_\alpha^{CN}(E,J,\pi)$ can be calculated

Problem: experiments only determine $\mathcal{P}(E) = \Sigma_{J,\pi}\, P_\delta^{CN}(E,J,\pi) \cdot P^{CN}_\gamma(E,J,\pi)$

→ Nuclear theory is needed to extract the individual $P^{CN}_\gamma(E,J,\pi)$.

The main challenges

- **Experiments**
  - **Experimental details to make sure the right compound is made and observing the decay products**
- **Reaction mechanism of the direct reaction**
  - **Do we form the compound nucleus as in the desired reaction?**
    - **Damping width of populated states must be larger than the gamma and neutron decay widths**



  - **Angular momentum populations**
    - **Use direct-reactions models to estimate J^{π} populations**
    - **Model γ-cascade**
- **Reaction cross section (probably known to ~5%)**
  - **Hauser-Feshbach to determine J^{π} populations for compound nucleus**
- **For (n,X) reactions we must pre-equilibrium back in**
- **Fission model following J^{π} populations**

Summary

- Surrogate reactions present us with an opportunity to extract important cross sections needed for astrophysics and Stewardship
  - This will permit a study of reactions on unstable nuclei before RIA
  - It will likely be an important tool with RIA (inverse kinematics)
  - The prospects of success look very promising
- There is still a need for theoretical support for these experiments
  - We need to understand direct-reaction mechanisms in order to determine the initial population of the compound nucleus
  - And how this differs from the simple case of an incident neutron
  - We need an accurate optical model to tell us what the reaction cross section is
  - We will likely need to know something about the decay of the final nucleus - do we need its spectroscopy to make surrogates work
    - Even if we do know the spectroscopy uncertainties in how the CN γ-decays may be worrisome
  - There is still pre-equilibrium